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RPPR Final Report
as of 15-Feb-2018

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Agreement Number: W911NF-14-1-0540

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Final Report for Period Beginning 01-Sep-2014 and Ending 31-Aug-2017

Title: Microscopic approaches to quantum non-equilibrium thermodynamics and information

Begin Performance Period: 01-Sep-2014

End Performance Period: 31-Aug-2017

Report Term: 0-Other

Submitted By: Anatoli Polkovnikov

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 2

STEM Participants: 4

Major Goals: Understanding dynamics and non-equilibrium steady states of macroscopic systems from microscopic principles. Connecting dynamics and information. Specific questions to be addressed: connections of microscopic description of quantum chaotic systems based on the random matrix theory (eigenstate thermalization) and macroscopic phenomena (both equilibrium and non-equilibrium). Understanding thermodynamics of periodically driven (Floquet) systems. Application of developed approaches to heat engines and other thermodynamic processes.

Accomplishments: See uploaded document.

Training Opportunities: List of partially supported graduate students:

Shainen Davidson (PhD, 2017)
Tiago Souza (PhD, 2016)
Marin Bukov (PhD, 2017)
P. Weinberg (current, PhD expected 2018)

Results Dissemination: Results of work were published in research papers and reviews (see uploaded PDF document for details). In addition they were reported in over fifty invited talks at domestic and international conferences, research seminars and colloquia.

Honors and Awards: Boston University supervisor of the year runner up award (2016);

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: Anatoli Polkovnikov

Person Months Worked: 3.00

Project Contribution:

International Collaboration:

Funding Support:

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International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Phillip Weinberg
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Marin Bukov
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Tiago Souza
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Shainen Davidson
Person Months Worked: 8.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Project Summary - Grant # W911NF-14-1-0540
(Final Report)**

Effort Title: Microscopic Approaches to Quantum Non-equilibrium Thermodynamics and Information

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Objective

Understanding dynamics and non-equilibrium steady states of macroscopic systems from microscopic principles. Connecting dynamics and information. Specific questions to be addressed: connections of microscopic description of quantum chaotic systems based on the random matrix theory (eigenstate thermalization) and macroscopic phenomena (both equilibrium and non-equilibrium). Understanding thermodynamics of periodically driven (Floquet) systems. Application of developed approaches to heat engines and other thermodynamic processes.

Approach

We employed a variety of analytical and numerical methods and in parallel were developing novel analytical and numerical approaches. In particular, we developed a new microscopic approach allowing one to simulate dynamics of quantum systems (including interacting fermions) by mapping them to classical systems living in higher-dimensional phase space [2]. We developed a new variational approach for minimizing dissipative losses in quantum and classical systems based on finding efficient approximate counter-diabatic protocols [5]. We wrote a comprehensive review connecting microscopic approach of random matrix theory and based on it eigenstate thermalization hypothesis with macroscopic postulates and laws of statistical mechanics and thermodynamics [9]. We also wrote two reviews describing approaches for engineering quantum and classical Floquet Hamiltonians as well as for the adiabatic state preparation [3, 16]. We wrote another review discussing applications of moving frame transformations in quantum and classical systems to finding emergent dynamical response of slowly driven systems [1].

Relevance to Army

We suggested several approaches allowing one to connect microscopic models describing quantum and classical systems with various macroscopic dynamical phenomena. Our ideas can be used for developing non-equilibrium phases with desired properties (Floquet engineering), suppressing dissipative losses, designing new efficient protocols for the state preparation. One can envision many various applications including those relevant to the Army coming from our research.

Accomplishments for Reporting Period

- Wrote a comprehensive review on quantum chaos and eigenstate thermalization and its applications to equilibrium and non-equilibrium thermodynamics [9]. Wrote a brief perspective on quantum thermalization for Science [8]. Wrote a joint experiment-theory

paper on studying connections between quantum and classical chaos in small systems of superconducting qubits [12]

- Wrote two reviews on Floquet systems: i) on general theory of Floquet systems and Floquet engineering [16] and on ii) adiabatic perturbation theory in Floquet systems [3].
- Developed theory of heating in periodically driven systems. Showed that at high frequencies heating is due to many-body resonances resulting in very non-trivial type behavior [11]. Developed a new approach for constructing integrable Floquet protocols, which lead to a strong suppression of heating [6]
- Extended celebrated Schrieffer-Wolff transformation to periodically driven systems [10] showing how theory of Floquet systems can be applied to find effective Hamiltonians in static systems (quantum and classical).
- Wrote an extensive pedagogical review/lecture notes on non-adiabatic response and geometry in quantum and classical systems [1]. Showed deep relations between non-adiabatic response coefficients: dynamical forces, added mass, work on the system and the quantum geometric tensor. Discussed how one can develop exact and approximate counter-diabatic driving protocols.
- Developed a new numerical method for simulating dynamics of interacting fermions by mapping it to classical dynamics of fermionic bilinears(strings). Showed that using this method we can accurately simulate a broad range of problems, in the regimes where there are no known competing methods [2]
- Showed that approximate counter-diabatic driving can be applied to complex systems greatly suppressing dissipation. Developed a new variational non-equilibrium principle, which is easy to implement and apply to both quantum and classical systems [5].

Results were published or submitted to high impact journals (Science, Nature Physics, Advances in Physics, Physics Reports, Physical Review Letters) and were reported in many domestic and international conferences, workshops, schools and research seminars.

Collaborations and Technology Transfer

- Collaborations (excluding students, postdocs, co-PI): A. Dutta (IIT Kanpur, India), D. Huse (Princeton), Y. Kafri (Technion, Israel), J. Martinis (UCSB, Google Inc.), P. Mehta (BU), E. Yuzbashyan (Rutgers)

Resulting Journal Publications During Reporting Period

Published

1. **Review:** M. Kolodrubetz, D. Sels, P. Mehta, A. Polkovnikov, Geometry and non-adiabatic response in quantum and classical systems, Physics Reports 697, 1-88 (2017)
2. S. M. Davidson, D. Sels, V. Kasper, A. Polkovnikov, Semiclassical Approach to Dynamics of Interacting Fermions, Annals of Physics, 384, 128-141 (2017).

3. **Review:** P. Weinberg, M. Bukov, L. D'Alessio, A. Polkovnikov, S. Vajna, M. Kolodrubetz, Adiabatic Perturbation Theory and Geometry of Periodically-Driven Systems, *Physics Reports* 68, 1-35 (2017)
4. H. Kim, A. Polkovnikov, E. A. Yuzbashyan, Gaussian ensemble for quantum integrable dynamics, *Annals of Physics* 381, 107-120 (2017)
5. D. Sels, A. Polkovnikov, Minimizing irreversible losses in quantum systems by local counter-diabatic driving, *PNAS*, Volume 114, 20 (2017)
6. V. Gritsev, A. Polkovnikov, Integrable Floquet Dynamics, *SciPost Phys.* 2, 021 (2017)
7. A. Nocera, A. Polkovnikov, A. E. Feiguin, Unconventional fermionic pairing states in a monochromatically tilted optical lattice, *Phys. Rev. A* 95, 023601 (2017)
8. A. Polkovnikov and D. Sels, Thermalization in small quantum systems, *Science*, 353, 752 (2016)
9. **Review:** L. D'Alessio, Y. Kafri, A. Polkovnikov, M. Rigol, From Quantum Chaos and Eigenstate Thermalization to Statistical Mechanics and Thermodynamics, *Advances in Physics* 65, 239 (2016)
10. M. Bukov, M. Kolodrubetz, A. Polkovnikov, Schrieffer-Wolff Transformation for Periodically Driven Systems: Strongly Correlated Systems with Artificial Gauge Fields, *Phys. Rev. Lett.* 116, 125301 (2016)
11. M. Bukov, M. Heyl, D. A. Huse, A. Polkovnikov, Heating and many-body resonances in a periodically driven two-band system, *Phys. Rev. B* 93, 155132 (2016)
12. C. Neill, P. Roushan, M. Fang, Y. Chen, M. Kolodrubetz, Z. Chen, A. Megrant, R. Barends, B. Campbell, B. Chiaro, A. Dunsworth, E. Jeffrey, J. Kelly, J. Mutus, P. J. J. O'Malley, C. Quintana, D. Sank, A. Vainsencher, J. Wenner, T. C. White, A. Polkovnikov, J. M. Martinis, Ergodic dynamics and thermalization in an isolated quantum system, *Nature Physics* 12, 1037–1041 (2016)
13. S. Sharma, U. Divakaran, A. Polkovnikov, A. Dutta, Slow quenches in a quantum Ising chain; dynamical phase transitions and topology, *Phys. Rev. B* 93, 144306 (2016)
14. T. Souza, M. Tomka, M. Kolodrubetz, S. Rosenberg, A. Polkovnikov, Enabling Adiabatic Passages Between Disjoint Regions in Parameter Space through Topological Transitions, *Phys. Rev. B* 94, 094106 (2016)
15. R. Mondaini and M. Rigol, Many-body localization and thermalization in disordered Hubbard chains, **Phys. Rev. A** 92, 041601(R) (2015).
16. Marin Bukov, Luca D'Alessio, Anatoli Polkovnikov, Universal High-Frequency Behavior of Periodically Driven Systems: from Dynamical Stabilization to Floquet Engineering, *Advances in Physics*, 64, 139-226 (2015)

Graduate Students Involved During Reporting Period

- Shainen Davidson (PhD, 2017)

- Tiago Souza (PhD, 2016)
- Marin Bukov (PhD, 2017)
- P. Weinberg (current, PhD expected 2018)